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Environmental Effect on the Associations of Background Quasars with Foreground Objects: II. Numerical Simulations

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ABSTRACT

Using numerical simulations of cluster formation in the standard CDM model (SCDM) and in a low-density, flat CDM model with a cosmological constant (LCDM), we investigate the gravitational lensing explanation for the reported associations between background quasars and foreground clusters. Under the thin-lens approximation and the unaffected background hypothesis , we show that the recently detected quasar overdensity around clusters of galaxies on scales of ~ 10 arcminutes cannot be interpreted as a result of the gravitational lensing by cluster matter and/or by their environmental and projected matter along the line of sight, which is consistent with the analytical result based on the observed cluster and galaxy correlations (Wu, et al. 1996). It appears very unlikely that uncertainties in the modeling of the gravitational lensing can account for the disagreement between the theoretical predictions and the observations. We conclude that either the detected signal of the quasar-cluster associations is a statistical fluke or the associations are generated by mechanisms other than the magnification bias.

Subject headings: clusters: general — cosmology: gravitational lensing — large-scale structure of universe

1. Introduction

Recently, a statistically significant correlation between distant quasars and nearby clusters of galaxies is detected on scales of ~ 10 arcminutes (Rodrigues-Williams & Hogan, 1994; Wu & Han 1995; Rodrigues-Williams & Hawkins, 1995; Seitz & Schneider 1995). It seems very unlikely that this correlation is due to the gravitational lensing of the quasars by the clusters, unless a considerably large velocity dispersion of $\sigma_v > 2000$ km s^{-1} is assumed for the clusters. This is because the association scales of $\sim 10'$ at $z \sim 0.2$ correspond to the "edges" of clusters of galaxies, where the influence of the gravitational lensing by cluster matter alone becomes small. Motivated by the remarkable quasar number excess around clusters, an attempt has been made to attribute the quasar-cluster associations to the gravitational lensing by the large-scale structures traced by clusters of galaxies, namely, the cluster environmental effect (Wu & Fang 1996a; Wu et al. 1996; hereafter Paper I and Paper II). A similar scenario has ever been suggested for the quasar-galaxy angular correlations on large-scales (Bartelmann & Schneider 1993). It appears that in the framework of gravitational lensing the cluster environmental matter described by the cluster-cluster and cluster-galaxy two-point correlation functions is insufficient to account for the quasar overdensity around clusters, if one adopts the unaffected background hypothesis, i.e., the observed quasar number counts as a whole have not been seriously contaminated by gravitational lensing.

However, a number of issues regarding the matter clustering around galaxy clusters may be overlooked if we only employ the two-point correlation functions. First, the biasing of the luminous matter with respect to the dark matter is not concerned. Second, a singular isothermal sphere model was presumed for the matter distribution of clusters, which is oversimple because of the presence of substructures. Third, the two-point cluster-cluster correlation function is inappropriate for the description of matter clustering within a

distance of ~ 5 Mpc from clusters. Yet, these problems can be easily dealt with by means of the cosmological numerical simulations. Indeed, clusters of galaxies usually reside in the intersections of filaments and pancakes, and the simulations of cluster formation provide an effective way to probe the environmental matter distributions traced by clusters. Alternatively, numerical simulations allow us to map all the matter inhomogeneities along the line of sight to the distant sources, giving rise to an estimate of the amplitude of the gravitational lensing effect by these matter clumps, i.e., the projection effects. It has been shown in a recent numerical study (Cen 1996) that the projection effects may significantly contaminate a number of physical quantities of clusters. Therefore, simulations can largely complement to analytic investigations in the study of cluster properties. In this paper we study the gravitational lensing effect on the quasar-cluster associations using a set of cosmological numerical simulations. Similar numerical techniques have been employed in the study of the gravitational lensing by microlenses (see, for example, Schneider et al. 1992), by clusters of galaxies (e.g. Bartelmann & Schneider 1991) and by large-scale structures (e.g. Cen et al. 1994; Wambsganss et al. 1996).

As the first step towards investigating the environmental effects on the quasar-cluster associations with numerical simulations, we adopt the "thin" lens approximation, i.e., we project all the matter inhomogeneities along the line of sight onto the lens (cluster) plane and make no distinction between the environmental effects and the projection effects. A more sophisticated treatment of the gravitational lensing effect by clusters and large-scale structures is to use the approximation of the multiple lens planes and the ray-shooting technique (Wambsganss et al. 1996; reference therein). For a transparent object at cosmological distance, its lensing magnification becomes significant only if its surface mass density Σ is comparable to the critical value of $\Sigma_{crit} = (c^2/4\pi G)(D_s/D_d D_{ds})$ (Turner et al. 1984), where D_d, D_s and D_{ds} are the angular diameter distances to the lens (cluster), to the background source (quasar) and from the lens to the source, respectively. To account for the

reported quasar overdensity around clusters on scales of $\sim 10'$ in terms of the gravitational lensing, it has been shown that a surface mass density of $\Sigma^* \approx 0.2\Sigma_{crit}$ is required (Paper I). We first examine whether the projected cluster environmental matter can reach a value as high as Σ^* (section 2). We then present a detailed computation of the magnification patterns induced by all the matter clumps and compute their resulting quasar enhancement factor q (section 3). Finally, we briefly discuss and summarize our results (section 4). Throughout the paper, we adopt a Hubble constant of $H_0 = 100$ km s^{-1} Mpc^{-1} and a flat cosmological model of $\Omega_0 + \lambda_0 = 1$, where Ω_0 and λ_0 denote the density parameters contributed by the cold dark matter and by the cosmological constant, respectively.

2. Cluster environmental matter distributions

We work with two cosmological models: the standard CDM model of $\Omega_0 = 1$ and $\lambda_0 = 0$ (SCDM) and a low-density, flat CDM model with a nonzero cosmological constant of $\lambda_0 = 0.7$ ($\Omega_0 = 0.3$) (LCDM). Their primordial density fluctuations are normalized by $\sigma_8 = 0.6$ for SCDM and $\sigma_8 = 1$ for LCDM, where σ_8 is the present rms mass contrast of a sphere of radius 8 Mpc. The normalizations are chosen such that both models predict cluster abundances similar to those observed (Jing & Fang 1994). Although SCDM is inconsistent with many observed properties of clusters of galaxies (e.g. Bahcall & Cen 1993), the model is still widely adopted as a working theory since it is simple and can qualitatively give us a sense of how the cosmic structures may look like. On the other hand, LCDM is one of the prevailing models that can quantitatively fit nearly all the observed properties of clusters including the mass function, the velocity dispersion distribution, the two-point correlation function and substructures around clusters (e.g. Bahcall & Cen 1993; White et al. 1993; Jing & Fang 1994; Jing et al. 1995; Kitayama & Suto 1996; Boute & Xu 1997).

We use a P^3M N-body code to generate the numerical simulations. For a detailed description of the simulations and of our identification of clusters, the reader is referred to Jing & Fang (1994). The simulations are performed in a cubic box of 128^3 Mpc^3 with periodic boundaries. A total of 64^3 particles is utilized and each particle has mass of $2.2 \times 10^{12}\Omega_0$ $\mathrm{M}_\odot$. The force resolution in our simulations is ~ 0.1 Mpc, and each rich cluster like the Abell one is composed of more than 100 particles. Since what we are interested in is the large angular correlations between quasars and clusters rather than the arclike images of background galaxies, high resolutions are not necessarily needed. To achieve a good statistical significance, we have run three realizations for SCDM and five realizations for LCDM, which yield roughly the same cluster populations.

For the present work, the most important quantity is the mass density $\rho(r)$ and the projected surface mass density $\Sigma(r)$. They are obtained using the Gaussian smoothing kernel $W(r, s)$ with a smoothing length s equal to the local mean particle separation. As examples, Fig.1 and Fig.2 display the 2-D mass distributions around a cluster of galaxies in SCDM and in LCDM respectively, produced by projecting a rectangular cylinder of 60 Mpc $\times$ 60 Mpc $\times$ 75 Mpc, where two surface mass density "filters" are employed: (a)$\Sigma \geq \Sigma^*$ and (b)$\Sigma \geq 0.1\Sigma^*$. The thickness of 75 Mpc is adopted to match the maximum separation in the cluster-cluster correlation function (Postman et al. 1992). It is immediately apparent from Fig.1 and Fig.2 that very sparse areas around clusters meet the requirement of $\Sigma \geq \Sigma^*$, i.e., clusters of galaxies do not inhabit the dense matter environments. In practice, all the points shown in Fig.1(a) and Fig.2(a) correspond to the cores of groups and clusters. The overall mean 2-D mass density in each field turns to be $\sim 10^{-3}$ g cm^{-2}, in accordance with our analytic estimate of the mean cluster environmental mass density (Paper II). So, our first intuitive impression based on the 2-D mass distributions in the vicinity of clusters is that there exists no massive uniform sheet around each cluster. However, it should be noted that this does not exclude the possibility of attributing the quasar-cluster associations to

the result of gravitational lensing. Indeed, the naive lensing model of a uniform mass sheet for cluster environmental matter distribution needs to be improved. There are numerous systems such as groups and poor clusters in the cluster fields [see Fig.1(b) and Fig.2(b)] and we have to investigate whether their combined lensing magnifications are capable of producing the observed quasar overdensity behind clusters.

EDITOR: PLACE FIGURE 1 HERE.

EDITOR: PLACE FIGURE 2 HERE.

3. Magnification patterns and quasar overdensity

We now determine the deflection angle of light $\boldsymbol{\alpha}$ at a position $\boldsymbol{\theta} = (\theta_x, \theta_y)$ from the cluster center $\boldsymbol{\theta} = 0$ by all the matter projected onto the cluster plane. To do this, we treat the matter distribution inside a cell as a uniform mass sheet which takes the value of the surface mass density at the grid. The total $\boldsymbol{\alpha}$ can be obtained by

$$\boldsymbol{\alpha} = \frac{4G}{c^2} D_d \sum_i \sigma_i \int_{s_i} \frac{\boldsymbol{\theta} - \boldsymbol{\theta}_i}{|\boldsymbol{\theta} - \boldsymbol{\theta}_i|^2} d^2\boldsymbol{\theta}_i, \tag{1}$$

where the integration and summation are performed inside each cell s_i with surface mass density σ_i and over all the cells on the cluster plane, respectively. The lens equation for a background source at redshift z_s and with angular position $\boldsymbol{\beta}$ is simply

$$\boldsymbol{\beta} - \boldsymbol{\theta} = \frac{D_{ds}}{D_s} \boldsymbol{\alpha}. \tag{2}$$

The Jacobian $\partial\boldsymbol{\beta}/\partial\boldsymbol{\theta}$ yields the magnification of an image at $\boldsymbol{\theta}$ of the background source

$$\mu(\boldsymbol{\theta}) = \left[1 - \frac{\phi^2 + \psi^2}{(\pi\Sigma_{crit})^2}\right]^{-1}, \tag{3}$$

where

$$\phi \equiv \sum_i \sigma_i \int_{s_i} \frac{(\theta_x - \theta_{ix})^2 - (\theta_y - \theta_{iy})^2}{|\boldsymbol{\theta} - \boldsymbol{\theta}_i|^4} d^2\boldsymbol{\theta}_i, \tag{4}$$

and

$$\psi \equiv - \sum_i \sigma_i \int_{s_i} \frac{2(\theta_x - \theta_{ix})(\theta_y - \theta_{iy})}{|\boldsymbol{\theta} - \boldsymbol{\theta}_i|^4} d^2\boldsymbol{\theta}_i. \tag{5}$$

For a given position $\boldsymbol{\theta}$, we calculate the magnification due to all the matter distributed within a square region of 15 Mpc $\times$ 15 Mpc surrounding $\boldsymbol{\theta}$. That is, a total of 150×150 cells has been used. Two examples of the matter distributions and the corresponding magnification patterns in a field of 15 Mpc $\times$15 Mpc centered at a cluster are shown in Fig.3 and Fig.4 for SCDM and LCDM, respectively. It is evident that, although all the matter in the field contributes to the magnification at a given position, the magnification patterns essentially follow the matter distributions. The high magnification usually appears in the cores of clusters, giving rise to the strong lensing events such as the arclike images of background galaxies.

EDITOR: PLACE FIGURE 3 HERE.

EDITOR: PLACE FIGURE 4 HERE.

Knowing the magnification patterns around each cluster, we are able to statistically compute the amplitude of quasar overdensity behind an ensemble of clusters due to the magnification bias. The mean quasar enhancement factor q for a quasar limiting magnitude B and within a projected distance r from a cluster center is

$$q = \frac{\int_o^r q_{\rm local}[B, \mu(r)] 2\pi r dr}{\pi r^2}, \tag{6}$$

in which $q_{\rm local}$ represents the local quasar enhancement factor (Narayan 1989):

$$q_{\rm local} = \frac{N_q(< B + 2.5 \log \mu)}{N_q(< B)} \frac{1}{\mu}, \tag{7}$$

and $N_q(< B)$ is the quasar number-magnitude relation. Supposing that the observed quasar number counts as a whole are unaffected by gravitational lensing (i.e. the unaffected background hypothesis), we can utilize the Boyle et al. (1988) quasar counts to estimate the value of q. Here, the radio-selected quasars and the variability-selected ones (Hawkins & Véron 1993) are not included.

Taking the typical redshifts of $z_s = 2$ for the background quasars and $z_d = 0.2$ for the foreground clusters and using a limiting magnitude of $B < 18.5$ which is comparable to the one in the measurements of quasar-cluster associations, we have calculated the enhancement factors around 30 rich clusters of galaxies selected randomly from our cluster catalogs with cluster masses ranging from $7.0 \times 10^{14} M_\odot$ to $1.5 \times 10^{15} M_\odot$ for SCDM and from $3.1 \times 10^{14} M_\odot$ to $1.2 \times 10^{15} M_\odot$ for LCDM, respectively. The mean value of q as a function of the projected distance from cluster centers has been illustrated in Fig.5. Aside from a weakly positive correlation between clusters and quasars at the central regions of clusters, we have not detected a remarkable overdensity of quasars around clusters out to cluster radii. This conclusion holds true for both SCDM and LCDM models. It appears unlikely that the statistical fluctuations in our simulations can account for the large discrepancy between the theoretically expected enhancements $q \approx 1$ and the observationally reported values $q \approx 2$ at a comoving distance of $r \approx 1 - 10$ Mpc.

EDITOR: PLACE FIGURE 5 HERE.

4. Discussion and conclusions

The present numerical study of the gravitational lensing effects by clusters and their environmental matter, together with our previous analytic investigations (Paper I and II), has resulted in a weak correlation between background quasars and foreground clusters

of galaxies on scales of $\sim 10'$. This suggests that the recently reported overdensity of quasars around clusters out to several cluster radii is not the result of the gravitational magnification bias unless (1) clusters of galaxies have a relatively large velocity dispersion up to 5000 km s^{-1} or (2) the observed quasar number-magnitude relation has been seriously contaminated by gravitational lensing. Recall that the similar conditions were required in order to account for the quasar-galaxy associations even on small scales of a few arcseconds (e.g. Webster et al. 1988; Narayan 1989). The first possibility implies that the cluster masses required for the lensing explanation of the quasar-cluster associations are of an order of magnitude higher than the known dynamical cluster masses. Although the dynamical analyses based upon hydrostatic equilibrium may underestimate cluster masses by a factor of ~ 2 as compared to the gravitational lensing method using arcs/arclets and weak lensing phenomena (Wu & Fang 1996b; reference therein), it is very unlikely that this mass discrepancy can be as large as 10 ! Therefore, such a possibility can be definitely excluded. As for the second possibility, the previous work (Schneider 1992; Pei 1995) has shown that the contamination of the quasar number counts from gravitational lensing by galactic matter is trivial. However, in the case of the quasar-cluster associations, the association area is usually a few tens percent of the total searching field, i.e., the association quasars are very common. So, the question remains open whether it is reasonable to inherit the unaffected background hypothesis in the study of the quasar-cluster associations.

Our estimate of the quasar enhancement factor may suffer from a number of uncertainties. The thin-lens approximation is in principle inappropriate for the description of large-scale matter distributions. It will be necessary in our subsequent studies to adopt a more realistic model that is composed of multiple lens planes. Also, we have used a uniformly smoothed mass distribution inside a cell in the calculation of deflection angle instead of the usually adopted pointlike model. In the latter case, all the mass inside a cell is assigned to its center. Our treatment avoids the occurrence of the artificially-induced strong

magnifications near the center of each cell (point mass). However, numerical simulations with high resolutions will be needed to overcome the softening of lensing ability due to the relatively large size (0.1 Mpc $\times$ 0.1 Mpc) for a cell.

From the observational point of view, although each measurement of the quasar-cluster associations claims that the detected quasar overdensity around clusters is not the result of statistical fluctuations or does not suffer from other observational selection effects, the real situations may be complicated. Among the four measurements, three different approaches are used to describe quantitatively the quasar-cluster associations because of the difficulty of obtaining the undisturbed or background quasar surface number density. If the definition of Seitz & Schneider (1995) is adopted, the quasar enhancement factors found by Rodrigues-Williams & Hogan (1994) and Rodrigues-Williams & Hawkins (1995) should be somewhat reduced. This may partially remove the discrepancy between the theoretical expectations and the observations. Alternatively, the null/negative associations were also detected in some searches (Wu & Han 1995; Seitz & Schneider 1995). However, those results were attributed to other mechanisms and hence, have not been included in the lensing analysis. It appears that current measurements of the quasar-cluster associations are probably biased. Actually, in contrast to the positive result, an anti-correlation between high redshift quasars and foreground clusters was reported many years ago (Boyle et al. 1988), which was interpreted as the result of the obscuration by the intracluster dust. As a number of subsequent observations has also provided the evidence against the excess number of quasars in the vicinity of clusters, further observations will be needed to improve the confidence level of different results before any definite conclusions can be drawn. Considering the same status and difficulty for the measurements and explanations of the quasar-galaxy associations (Zhu et al. 1997; Fried 1997; reference therein) and the quasar-quasar associations (Burbidge et al. 1997), we believe that all the association

problems reported thus far might have a common origin: either the observations have not detected the associations of background quasars with foreground objects as a result of gravitational lensing, or the associations are generated by some mechanism other than the gravitational lensing if the observed quasar number counts are not very much different from the intrinsic ones.

Finally, because the discrepancy in the quasar enhancement factors between the theoretical expectations in terms of gravitational lensing and the observations is very large, it is unlikely that the conclusions reached in this paper can be significantly affected by utilizing other cosmological models instead of SCDM and LCDM

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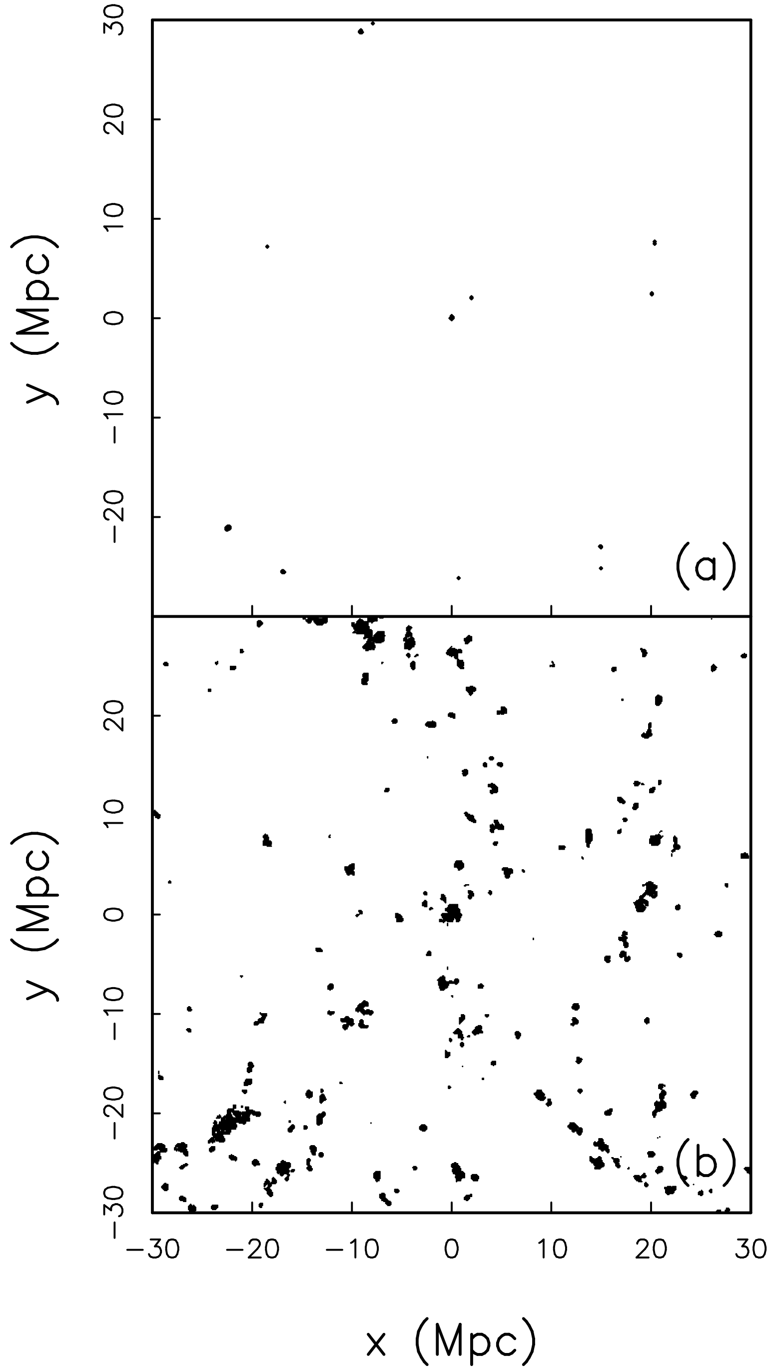
Fig. 1.— An example of the SCDM generated 2-D matter distributions in a square region of 60 Mpc $\times$ 60 Mpc centered at a cluster, obtained by projecting all the matter inside a cube with comoving length of 75 Mpc. (a)Surface mass density $\Sigma \geq \Sigma^*$ and (b) $\Sigma \geq 0.1\Sigma^*$, where Σ^* is the surface mass density required to produce the reported amplitude of quasar overdensity around clusters of galaxies in the framework of gravitational lensing.

Fig. 2.— The same as Fig.1 but for LCDM.

Fig. 3.— An example of the 2-D matter distribution (a) and the corresponding magnification patterns (b) around the same cluster shown in Fig.1(b) in a square region of 15 Mpc $\times$ 15 Mpc. The void regions, the shadows and the darkened areas in (b) represent $\mu < 1.001$, $1.001 \leq \mu \leq 1.005$ and $\mu > 1.005$, respectively.

Fig. 4.— The same as Fig.3 but for the cluster in Fig.2.

Fig. 5.— The enhancement factor q of optically selected quasars with $B \leq 18.5$ versus searching distance r from cluster centers. A total of 30 rich clusters has been used in each model (SCDM and LCDM) and 1σ error bars have been shown.



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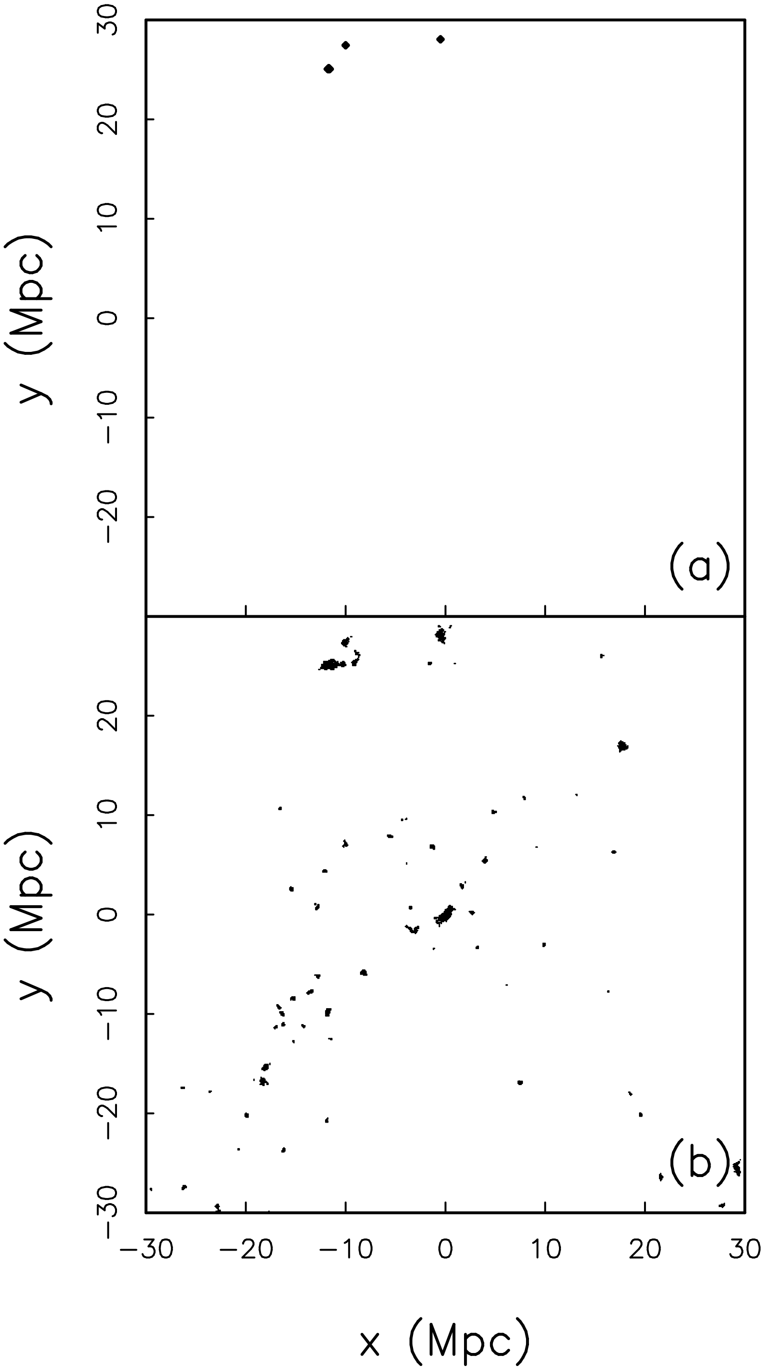

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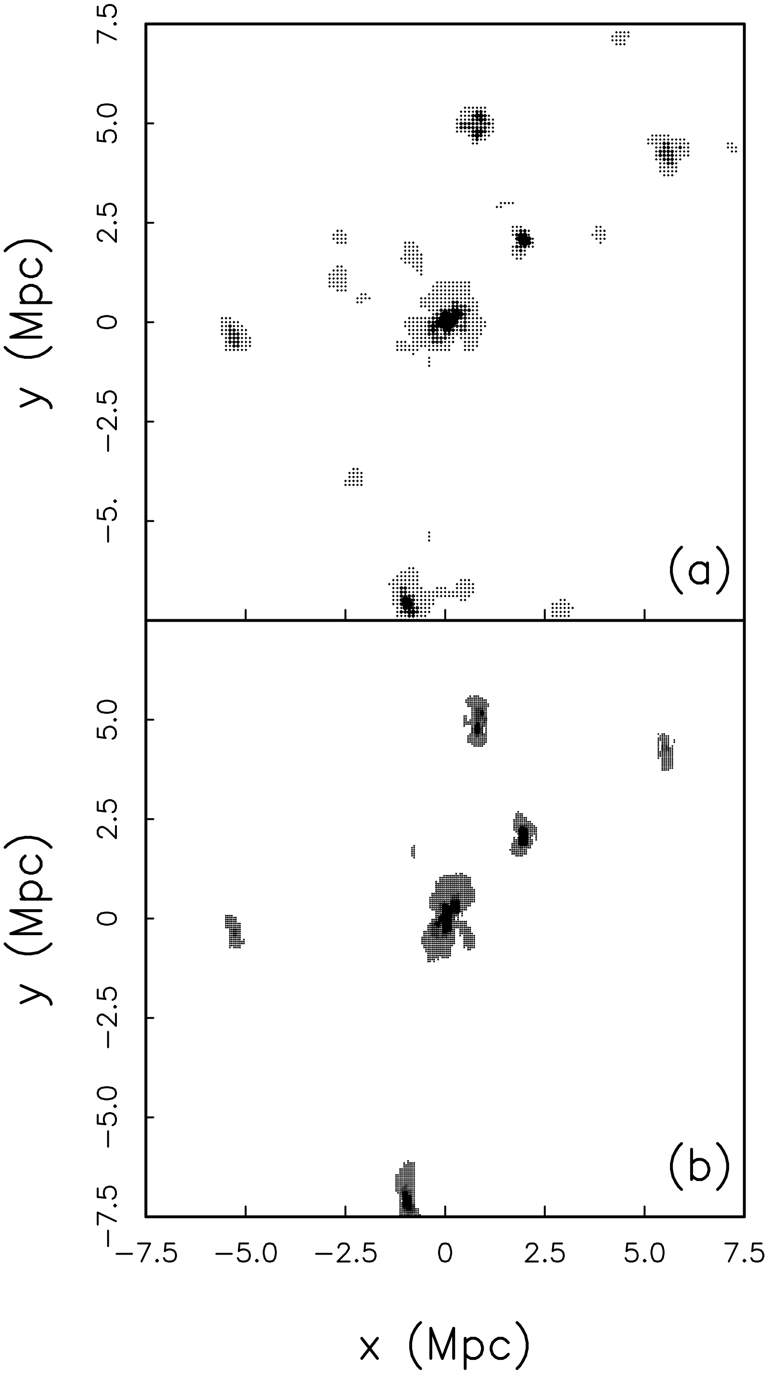
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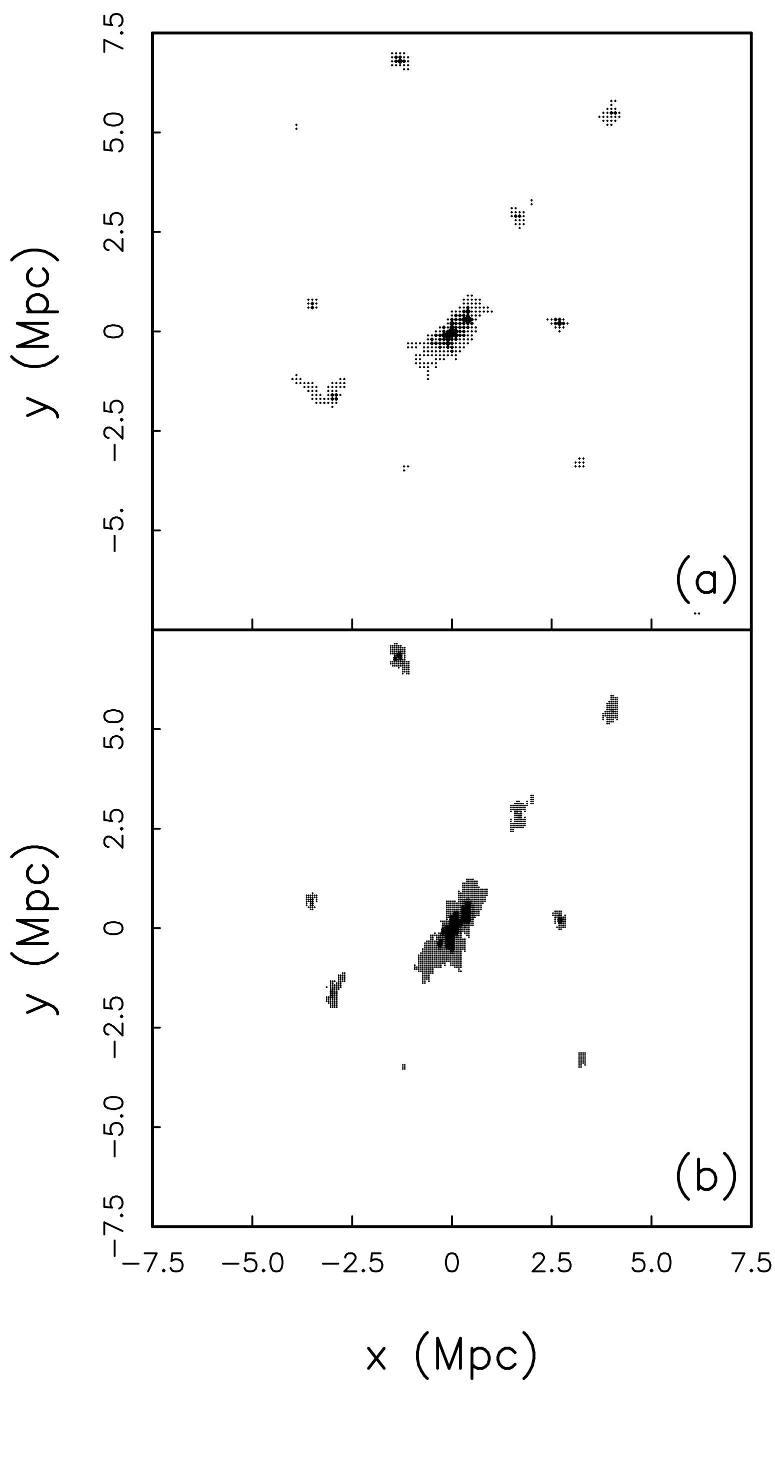

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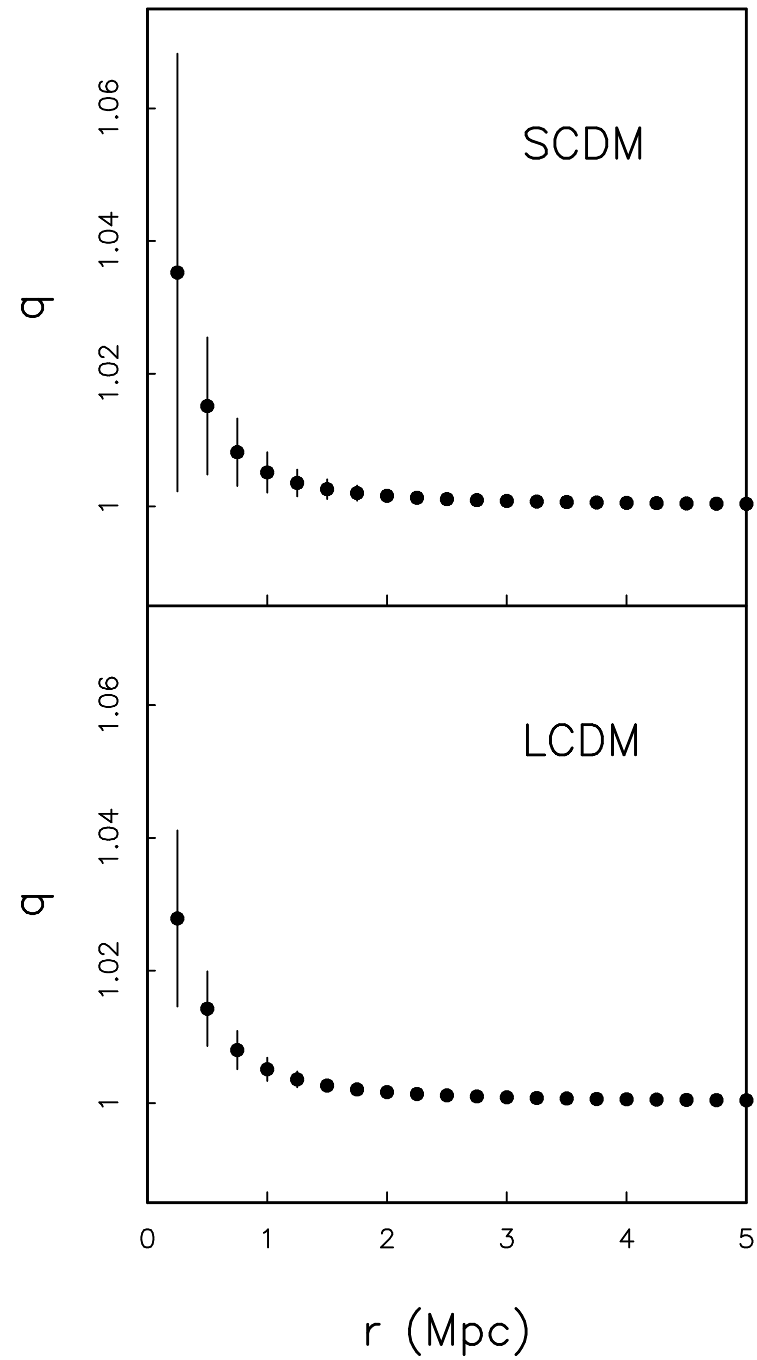
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